

MC analysis with Rivet

Analysis prototyping and re-re-re-interpreting

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University of Glasgow

MC4EIC workshop
19 Nov 2021



University
of Glasgow

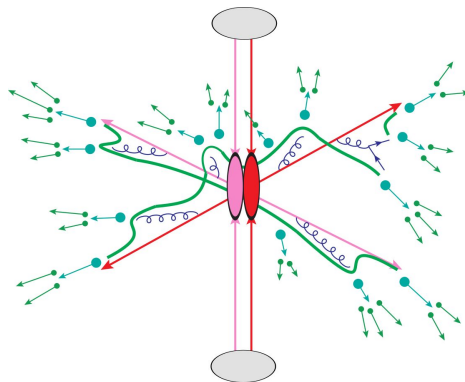
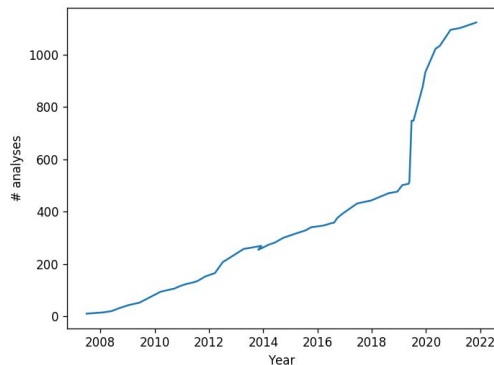
Outline

- ❖ The Rivet toolkit and project
- ❖ Origins and generic analysis preservation
- ❖ Existing applications: MC tuning, BSM searches
- ❖ Rivet for heavy ions and EIC
- ❖ More features: systematics weights and detector sim
- ❖ The future of Rivet
- ❖ Joining in

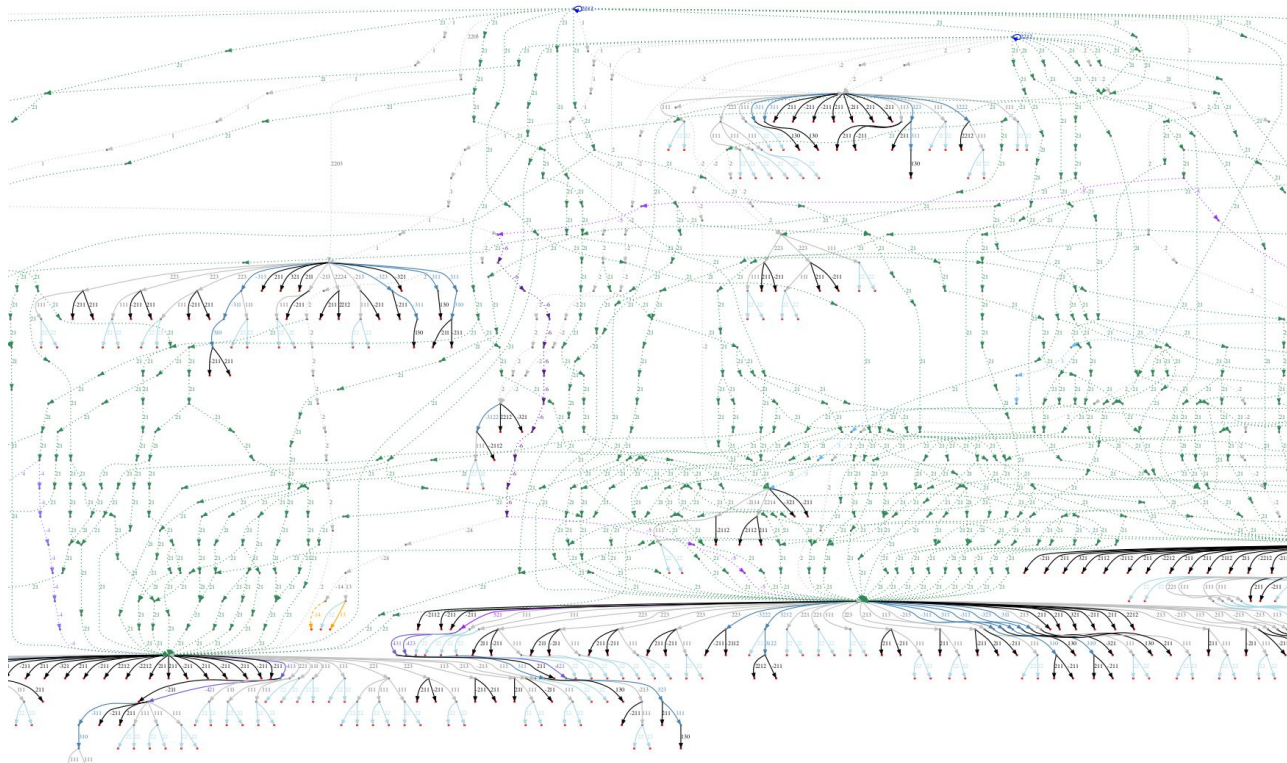


What is Rivet?

- ❖ The “LHC standard” MC analysis toolkit
- ❖ More broadly a project to preserve the logic of HEP data analyses and further expt-pheno collaboration
- ❖ Containing some predictable / less-predictable things:
 - An **event loop**
 - Physics object / **observable calculators**
 - Fiducial / **generator-independence** emphasis
 - Integration with **HepData**
 - Transparent **weight-stream handling**
 - **1000+ analyses!**
- ❖ Rivet now sits at the centre of a web of analysis reinterpretation tools, linking experiment to theory
- ❖ **But why?**



Just part of an LO top event. $HI \Rightarrow$ far worse!



Want to avoid physicists needing to rewrite graph algorithms, and know all the conventions, pitfalls, physical/debug distinctions, ...

From HZTool to Rivet


❖ The idea of preserving experimental analyses for MC validation was born out of HZTOOL

- HERA (H1 and ZEUS) DIS and photoproduction
- Probing **low- x , semi-perturbative physics**:
DIS with $Q^2 \sim 4 \text{ GeV}^2$; jet $p_T \sim 5 \text{ GeV}$; diffraction
- **Many “state of the art” models only in MCs**
- Much confusion about comparing like-with-like between generators, experiments, and analyses
- **HZTool** (Fortran) for cross-experiment comparisons of similar measurements modulo cut differences

❖ Direct line to Rivet, 10 years later: “HZ mark two”

- UK e-science funding; adopted by EU **MCnet network**


Future Physics at HERA
 Workshop, DESY Hamburg, Sept. 95 to Sept. 96



Aim: Study of future physics potentials at HERA in collider and fixed target modes, including high luminosity, polarized beams and nuclei.

Proceedings of the Workshop

[Old home page](#) and [workshop meetings](#)




Working Groups:

- Structure Functions
- Electroweak Physics
- Beyond the Standard Model
- Heavy Quark Production and Decay
- Jets and High E_T Phenomena
- Diffractive Hard Scattering
- Polarized Protons and Electrons
- Light and Heavy Nuclei in HERA
- HERA Upgrades and Impacts on Experiments

Organizing Committee:
 Gunnar Ingelman, Uppsala/DESY (Chairman)
 Albert De Roeck, DESY
 Robert Klanner, DESY

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Advisory Committee:
 W.Buchmüller, J.Feltesse, A.Levy,
 H.Schröder, J.van den Brand, A.Wagner



HERA B

Email: heraws96@mail.desy.de

If you are using mosaic, click [here](#).

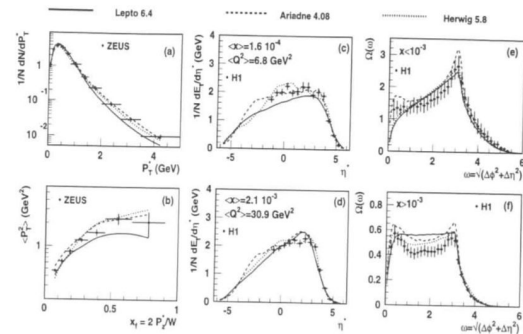


Figure 1: The transverse momenta dN/dp_T (a) and the 'seagull' plot $\langle P_T^2 \rangle \times x_F$ (b) of single particles in the positive hemisphere of the hadronic center of mass. The transverse energy flow $dE_T/d\eta$ in a low (c) and high (d) x and Q^2 bin. The transverse energy-energy correlations for $x > 10^{-3}$ (e) and $x < 10^{-3}$ (f).

Lessons learned from HZTool

❖ A simple/obvious idea, with surprising impact

- Reproducing a key plot (or not) is *powerful*
- *⇒ understand physics, communicate issues, improve MCs*
- *A common language for phenomenology and experiment*

❖ But...

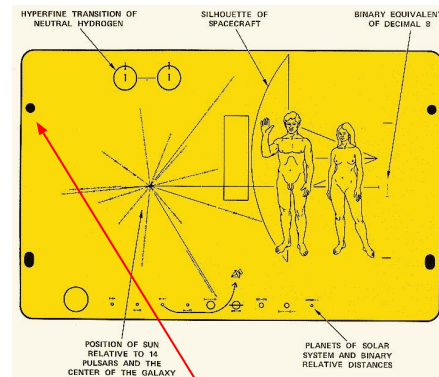
- Obvious to use partons, bosons, etc. direct from the event graph
- Frequently unphysical, depend on approximations. May not even exist!
- HZTool full of cryptic “if HERWIG, if PYTHIA, if ...” code
- Adding a new generator meant patching ~all analyses!
- *⇒ predict “real” observables, from well-defined final states*

❖ Standardisation: boring but important

- (physical) event format conventions, statuses, PDG particle numbering, etc.

❖ Scalability

- Lots of expensive operations are repeated: sharing calculations is essential



Designing Rivet

❖ Ease of use

- **Big emphasis on “more physics, less noise”!**
- Minimal boilerplate analysis code, HepData sync
- Event loop and histogramming basically familiar
- **Tools to avoid having to touch the raw event graph**

❖ Embeddable

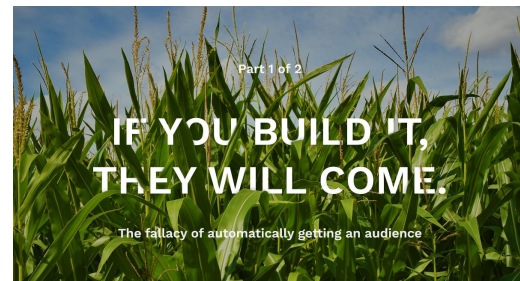
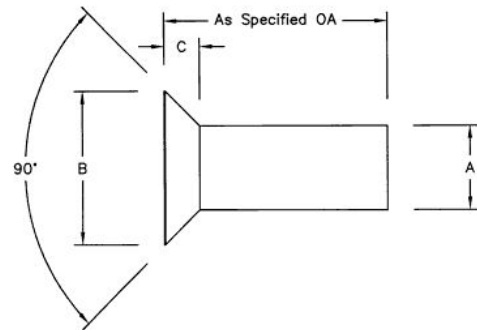
- OO C++ library, Python wrapper, sane user scripts
- Generator independence: communication via HepMC
 - Note HepMC3 HI-support efforts
- Analysis routines factorised: loaded as “plugins”

❖ Efficient

- **Avoid recomputations via “projection” caching system**

❖ Physical

- **Measurements primarily from final-state particles only**



Event-generator tuning

Event generators all have dirty secrets. Usually non-perturbative ones... $O(30+)$ parameters

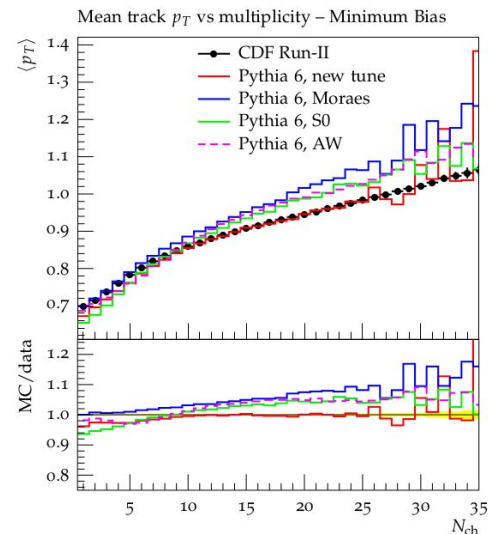
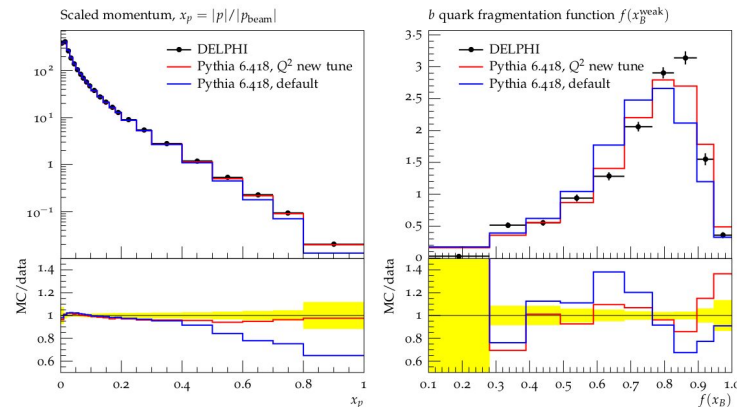
- ❖ First systematic hadron collider “tunes” of PYTHIA6 by Rick Field for CDF ~ 2001

- Tune A, Tune D, Tune DW, etc. etc.

- ❖ Limited datasets, variation by hand

- Rivet and its analyses were a game-changer
 - You only know a model is incapable when you’ve scanned its whole param space... and then the argument is over

- ❖ The “Professor” tunes, 2008; and...

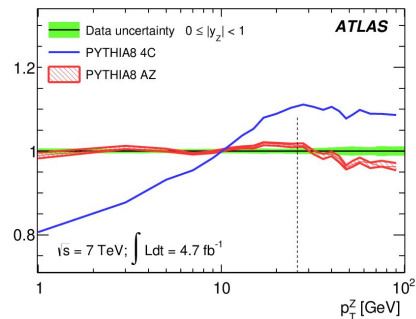
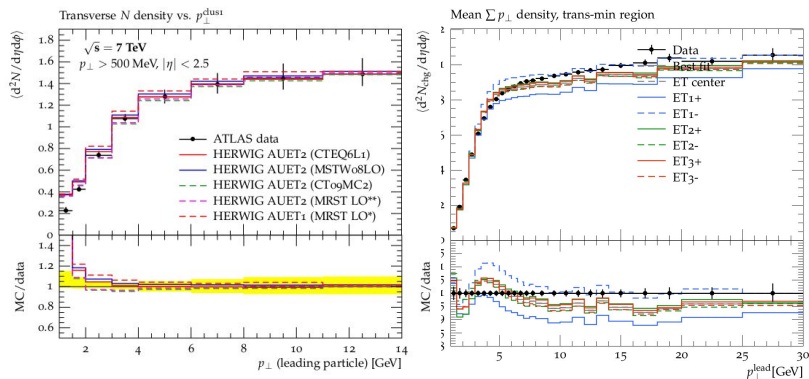


Tuning and beyond

Huge pre-LHC soft-QCD uncertainties:

- ❖ Tuning ~required Rivet analyses from expt
- ❖ Feed in to underlying event, pile-up, etc.
 - Better tunes \Rightarrow better analysis, better results
 - **Impact:** LEP and Tevatron analyses published for ~ 10 years suddenly got used! And cited...
 - \Rightarrow ATLAS tunes, CMS tunes, **eigentunes**
 - \Rightarrow Rapid responses to preliminary data
 - **Model development:** matching & merging, addition of energy evolution & colour-reconnection to Herwig, ...

- ❖ Recently, also use of Rivet's large analysis collection for *BSM*; + $H \rightarrow b\bar{b}$ prototyping:

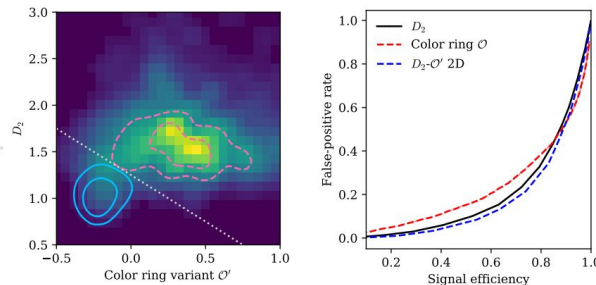


Download:

- PDF
 - Other formats
- (license)

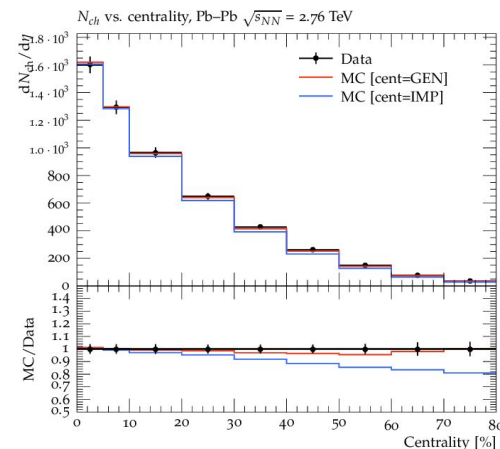
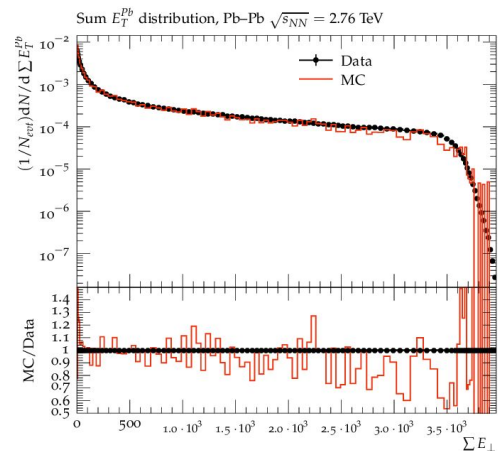
Ancillary files (details):

- VHPULL.cc
- VHPULL.info
- VHPULL.plot



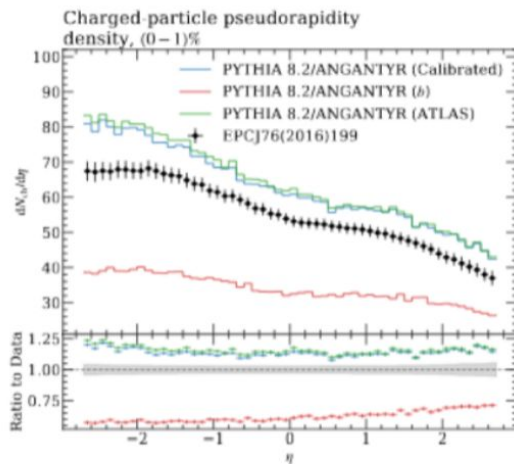
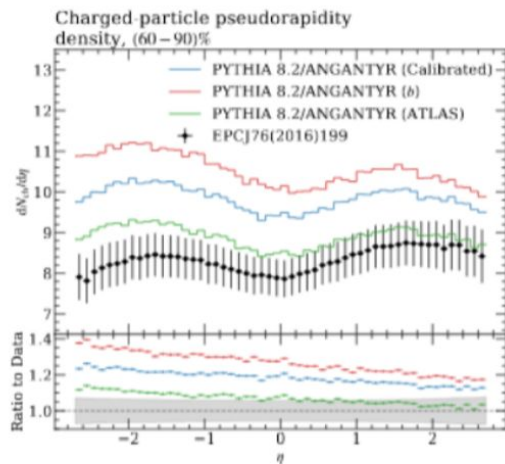
Heavy-ion physics preservation

- ❖ “Adding heavy-ion support” sounds trivial!
- ❖ **Actually nuanced, requiring structural evolution**
 - HI observables often require centrality-calibration curves: we need a 2-pass run. That wasn’t planned
 - And event/event correlations... centrality-binned!
 - Need swappable definitions: few HI generators are general-purpose enough to do e.g. both forward E_T and jet quenching
- ❖ **All supported “out of the box” since v3**
 - Paper: <https://arxiv.org/abs/2001.10737>
 - Core development tool for Pythia/Angantyr, authors and ALICE (etc.) collaborators providing analyses
- ❖ *Common tool \Rightarrow discuss & evolve HI MC standards*



Centrality

- Centrality is a key concept in HI physics
- Theory-level definition different to experimental level
- Subtle biases, especially in pA



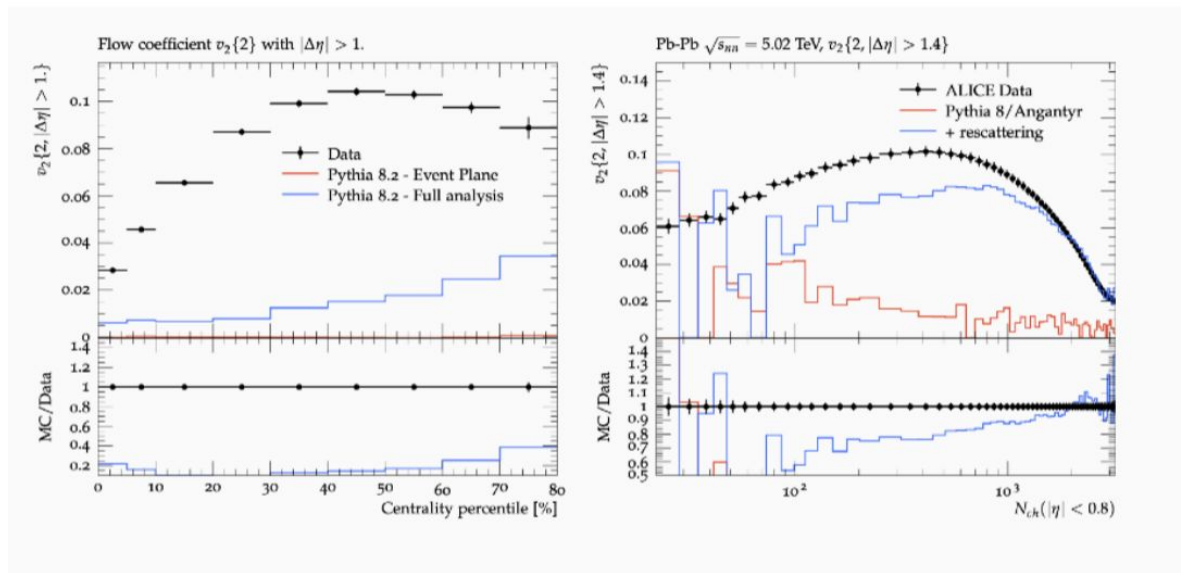
Rivet for HI includes:

- Centrality calibration
- Analysis options to select calibration

Flow observables

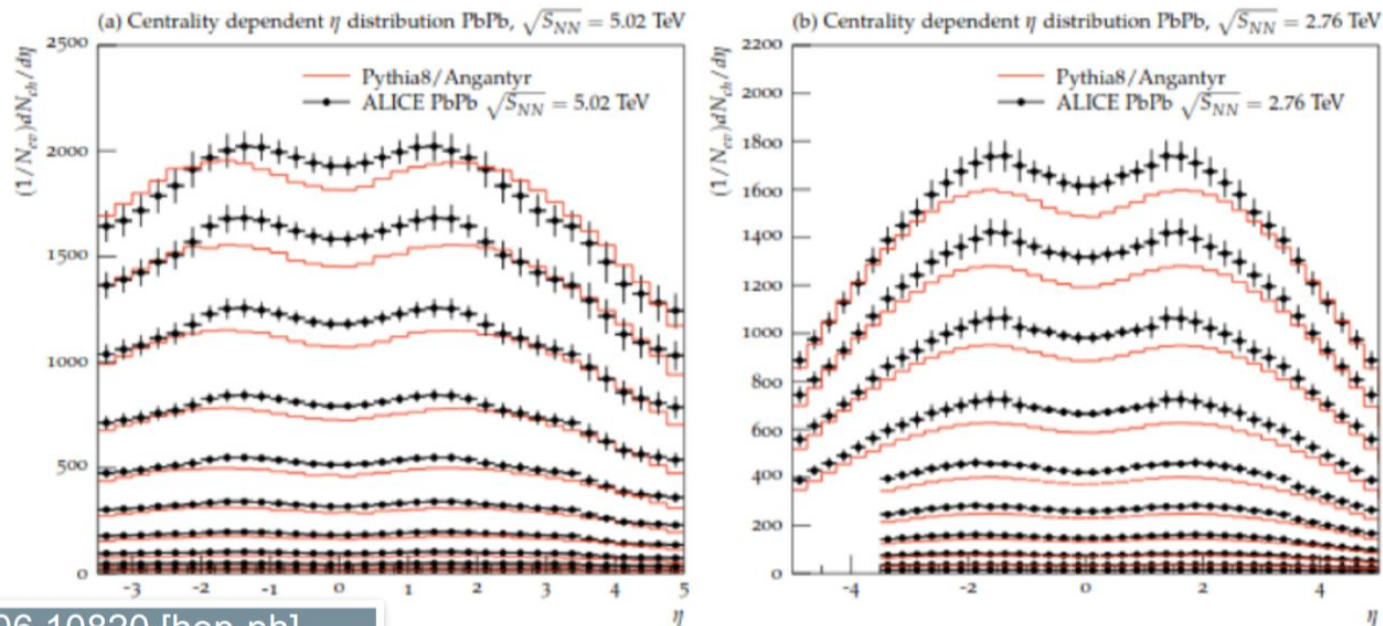
Rivet for HI includes:

- Generic framework for calculating flow observables, energy correlators and cumulants
- Already analyses using them: eg ALICE 2016 I1419244 and ALICE 2019 I1723697



Triggers and particle definitions

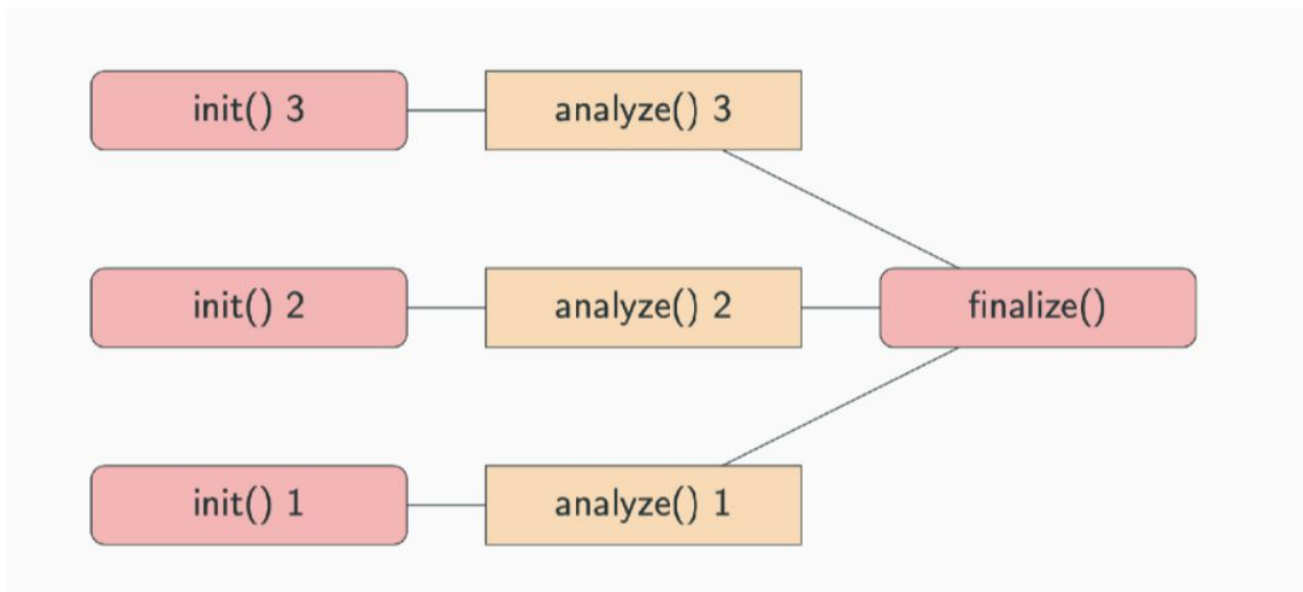
- Getting these right are important, can be $\sim 10\%$ effect, similar to MC accuracy
- Rivet for HI includes ALICE::Trigger and ALICE::PrimaryParticle projections



Angantyr: 1806.10820 [hep-ph]

Parallel runs and recombination

- Parallelization is necessary but potentially difficult: flavour ratios, R_{AA} , flow...
- Solution: rivet-merge before finalization
- Let analyser implement merging → perfect run combination



HI community preservation!

- ❖ Great “spontaneous” engagement from within HI. Several productive workshops

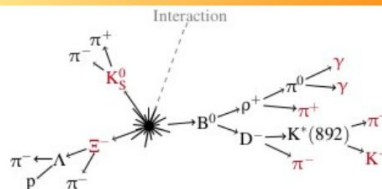
Summary

1. Data getting into HEPData

2. Build your own undergraduate army

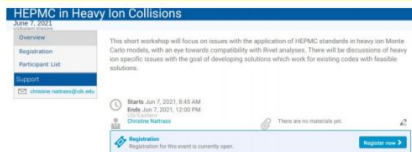


3. Primary particle definition



4. Validation Procedure

5. HEPMC output may have some issues



<https://indico.bnl.gov/event/10966/>

- ❖ HepData, Rivet
- ❖ Better ex/ph communication
- ❖ Faster model/data comparisons
- ❖ Addressing issues with formats and incomplete models
- ❖ Undergrad army!
- ❖ <https://indico.cern.ch/event/1022351/>

Also for EIC: ep /DIS/photoproduction

❖ Recent pushes to include more ep analyses

- Remember Rivet origins in HERA HZTool?
- 2 analyses and DIS boosted frames since the beginning
- Older attempt to port HZTool analyses to Rivet flopped: ~little interest → semi-useful RivetHZTool package
- Now changing, largely due to EIC

❖ 8+2 new HERA routines in v3.1.5

- Supplied via preservation effort by Andrii Verbytskyi
- More to come...

❖ 18 more from DESY summer students

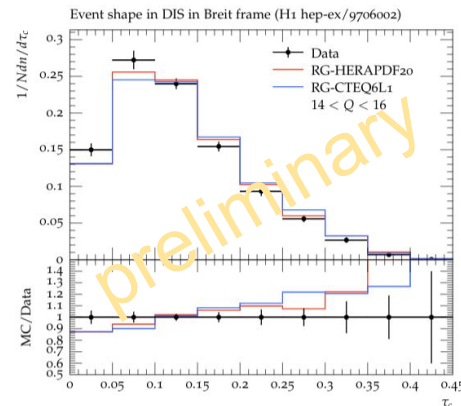
- 2019 Rivet/DESY preservation workshop: refinements in fiducial machinery for DIS
- Rivet-based preservation programme in summer 2021
- Coming soon... v3.1.6 in ~Feb 2022?

Rivet, RivetHZTool and HERA

A validation effort for coding HERA measurements for Rivet

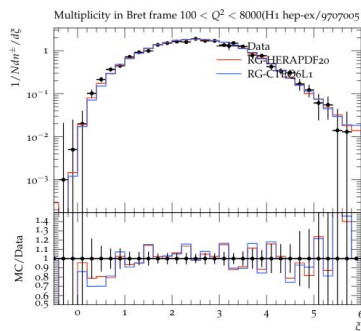
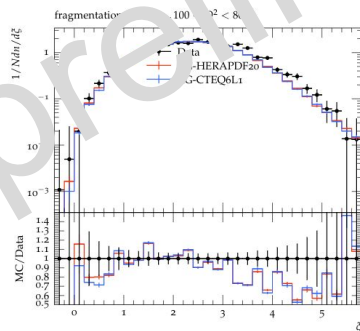
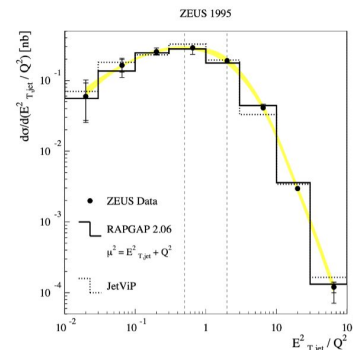
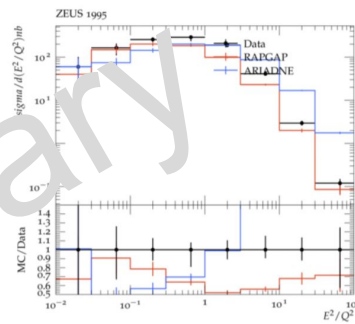
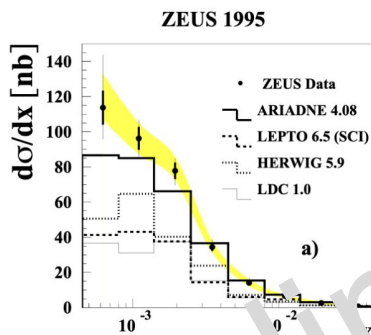
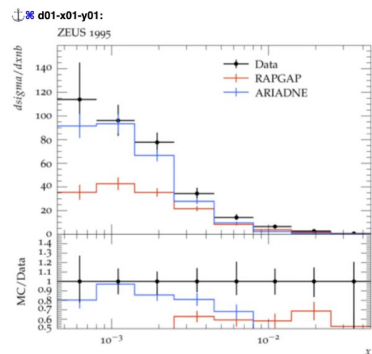
Muhammad Ibrahim Abdulhamid⁸, Andrea Achilleos,
Giorgia Bonomelli, Aryan Borkar¹⁴, Madhav Chithirasreemadam,
Maksim Davydov¹⁶, Keila Moral Figuerca, Alejandro B. Galván,
Susie Kim, Kritsanon Koehnckok, Luca Marsili¹³,
Ariadna León Quirós, Narmala Kumova, Jacob Shannon,
Suraj Singh¹⁴, Can Süslü¹², Nataporn Trakulphorm, Danielle Wilson,
Wenting Zhang

A. Berruete, Martinez², A. Buckley⁹, C. Bierlich¹⁵,
J. M. Butterworth¹³, L.I. Estevez Banos², C. Gütschow¹¹, H. Jung²,
M. Mendizabal², S. Taheri Monfared², S. Plätzer¹⁰, S. Schmitt, P. van
Mechelen⁴, Q. Wang^{2,7}, G. Watt¹⁷, M. Wing¹¹, H. Yang^{2,7}



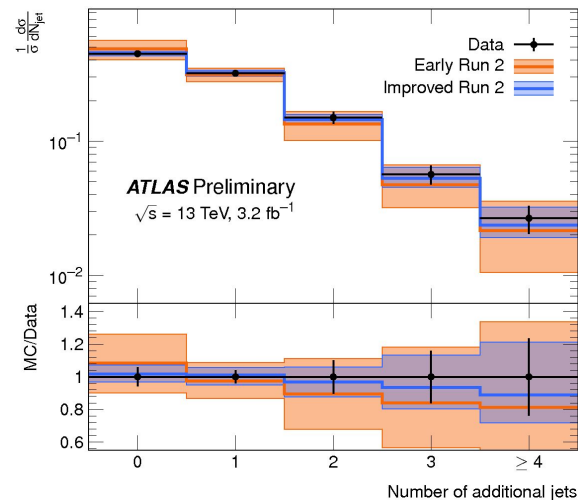
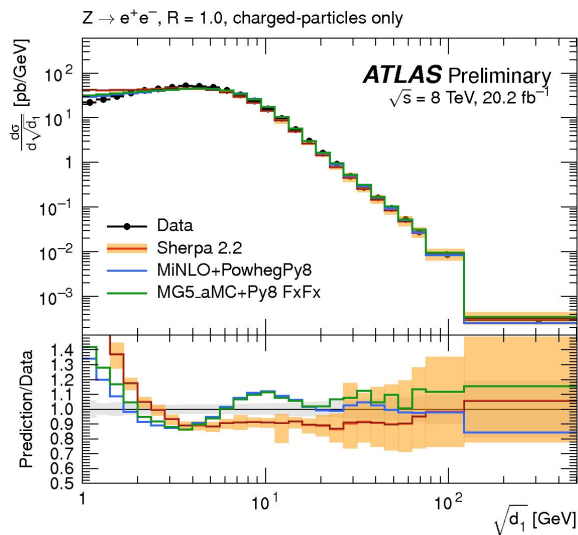
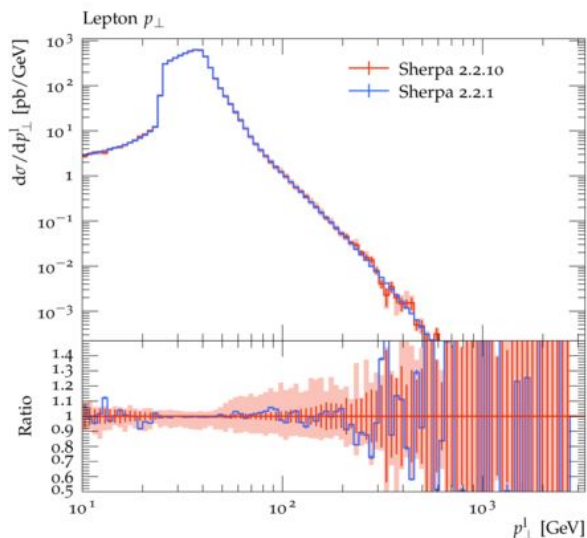
More prelim HERA ep outputs

Analyses on everything from jet rates, to event shapes, E_T flow, K rates, b production, D and inclusive fragmentation, ...



Precision: theory systematics via multiweights

ATLAS MC studies have been a significant driver of this feature (thanks to Chris Gutschow)

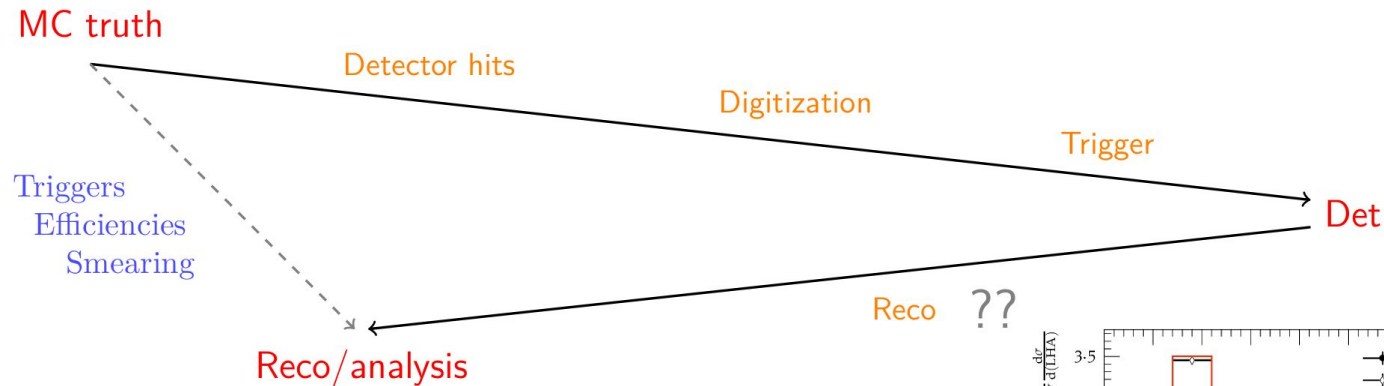


Weight-naming standardisation underway via MCnet

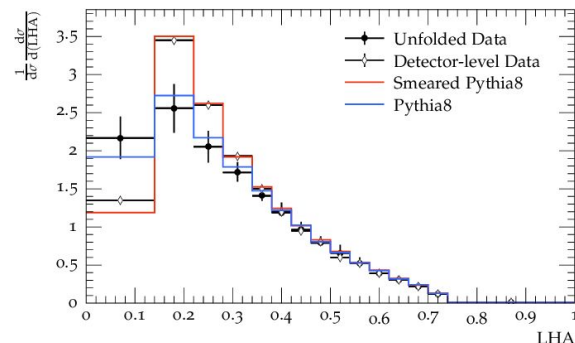
Detector emulation (but please unfold by preference!)

❖ Detector smearing built on Rivet's projection system — for reco-level analyses

- developed based on Gambit ColliderBit experience: no need for “full fast-sim”



- like Delphes, but more flexible & can be *analysis-specific* \Rightarrow MA5 “SFS” mode
- flexibility allows e.g. “tuned” jet-substructure smearing, systematics studies, ...



The future of Rivet

- ❖ **Vision: Rivet as a standard for “truth-level” observables, across collider physics**
 - The EIC programme is absolutely part of that target
- ❖ Not just standalone, but as a library in pheno & experiment frameworks, too: standard MC definitions, seamless systematics handling, etc.
- ❖ At its core: a **physics-oriented** system for physicists to **compare MC predictions to one another and to data, on many simultaneous observables, in myriad ways**
We don't know all the use-cases yet!
- ❖ **Challenges:**
 - Extension of HepData and other community infrastructure for ever more precise data. Even our compressed data format is struggling with the volume of analyses and data.
Work needed/underway on multiweight-oriented data format and tools
 - Improved, modernised visualisation and exploration
 - Preserving MVAs: BDT and NN in vanilla C++?

Getting & using Rivet

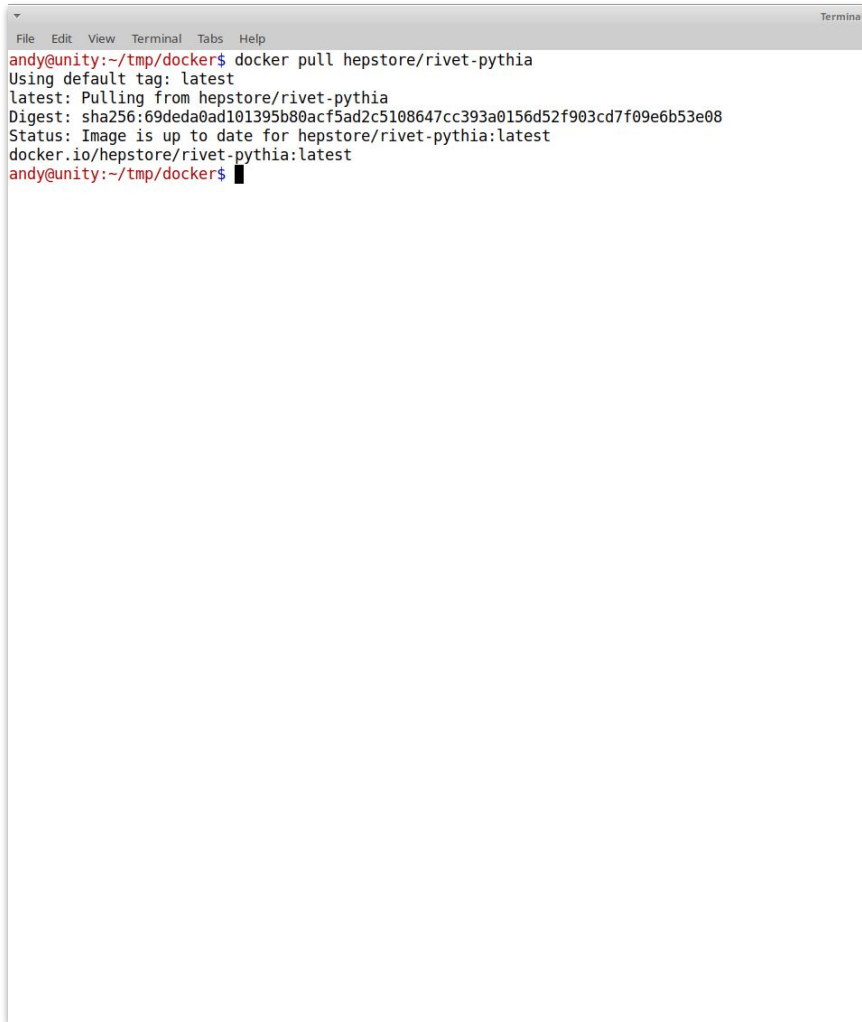
**Lightweight analysis preservation
is valuable... and easy to start**

As either a “user” or analysis
author, the barrier is lower than
ever: we recommend using our
Docker images to get started

Ideal for student projects!

Tutorials available from the
[Rivet website](#), a **walkthrough** in
the [R3 paper](#)

Imitation the highest form of
flattery ⇒ copy an existing analysis!

A terminal window titled "Terminal" with a menu bar (File, Edit, View, Terminal, Tabs, Help). The terminal shows the command "docker pull hepstore/rivet-pythia" being executed. The output indicates the image is pulled successfully from the latest tag, showing the digest and status. The prompt returns to the user.

```
andy@unity:~/tmp/docker$ docker pull hepstore/rivet-pythia
Using default tag: latest
latest: Pulling from hepstore/rivet-pythia
Digest: sha256:69deda0ad101395b80acf5ad2c5108647cc393a0156d52f903cd7f09e6b53e08
Status: Image is up to date for hepstore/rivet-pythia:latest
docker.io/hepstore/rivet-pythia:latest
andy@unity:~/tmp/docker$
```

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Status: Image is up to date for hepstore/rivet-pythia:latest
docker.io/hepstore/rivet-pythia:latest
andy@unity:~/tmp/docker$ docker run -it --rm -v $PWD:/out hepstore/rivet-pythia
root@fd5bf204ef9e:/work#
```


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```
File Edit View Terminal Tabs Help
root@d8c06acf8f66:/work# cp /usr/local/share/Pythia8/examples/main93.cmd py.cmd
root@d8c06acf8f66:/work# nano py.cmd
```

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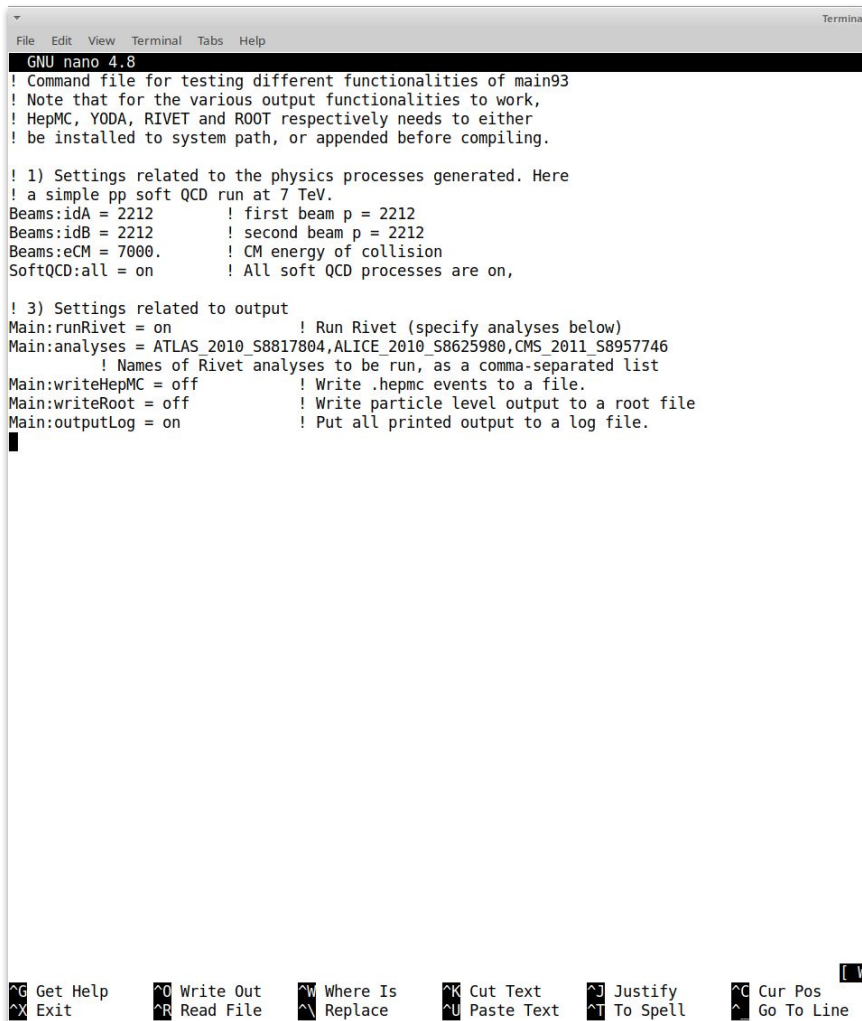
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```
GNU nano 4.8
! Command file for testing different functionalities of main93
! Note that for the various output functionalities to work,
! HepMC, YODA, RIVET and ROOT respectively needs to either
! be installed to system path, or appended before compiling.

! 1) Settings related to the physics processes generated. Here
! a simple pp soft QCD run at 7 TeV.
Beams:idA = 2212      ! first beam p = 2212
Beams:idB = 2212      ! second beam p = 2212
Beams:eCM = 7000.     ! CM energy of collision
SoftQCD:all = on      ! All soft QCD processes are on,

! 3) Settings related to output
Main:runRivet = on     ! Run Rivet (specify analyses below)
Main:analyses = ATLAS_2010_S8817804,ALICE_2010_S8625980,CMS_2011_S8957746
! Names of Rivet analyses to be run, as a comma-separated list
Main:writeHepMC = off  ! Write .hepmc events to a file.
Main:writeRoot = off   ! Write particle level output to a root file
Main:outputLog = on    ! Put all printed output to a log file.
```

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File Edit View Terminal Tabs Help
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root@d8c06acf8f66:/work# nano py.cmd
root@d8c06acf8f66:/work# pythia8-main93 -c py.cmd -n 10000
```

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root@d8c06acf8f66:/work# cp /usr/local/share/Pythia8/examples/main93.cmnd py.cmnd
root@d8c06acf8f66:/work# nano py.cmnd
root@d8c06acf8f66:/work# pythia8-main93 -c py.cmnd -n 10000
```

Getting & using Rivet

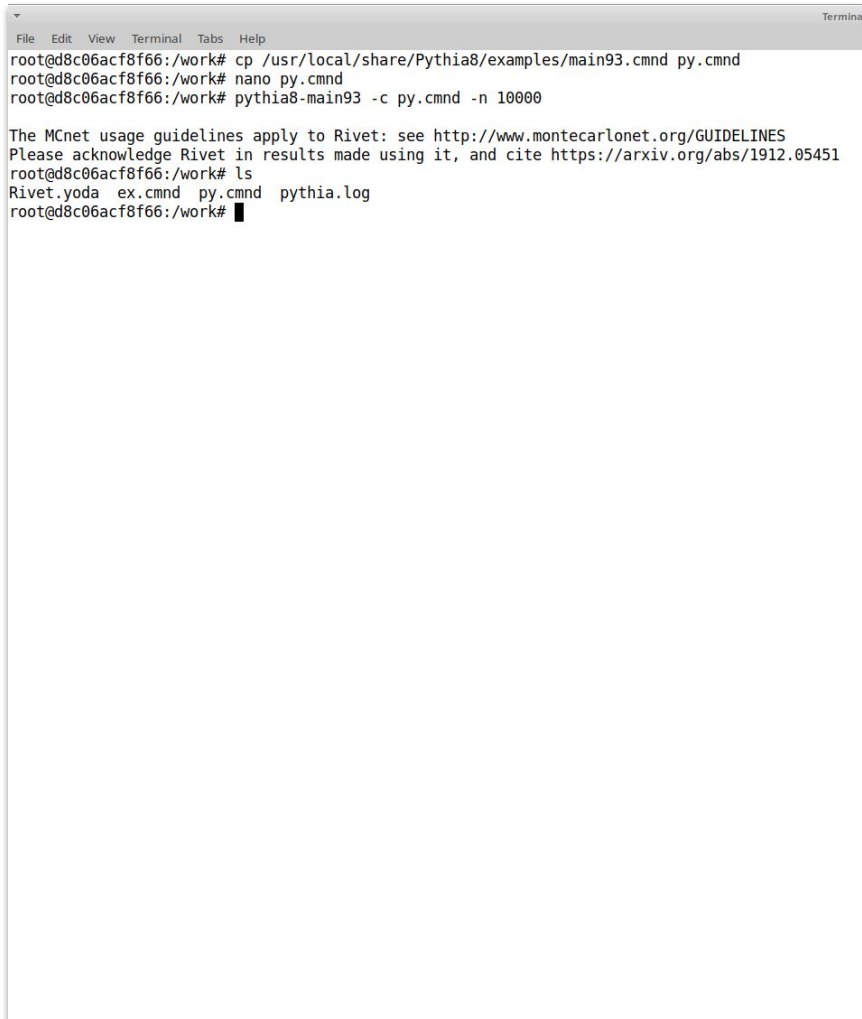
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root@d8c06acf8f66:/work# pythia8-main93 -c py.cmd -n 10000

The MCnet usage guidelines apply to Rivet: see http://www.montecarlonet.org/GUIDELINES
Please acknowledge Rivet in results made using it, and cite https://arxiv.org/abs/1912.05451
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root@d8c06acf8f66:/work#
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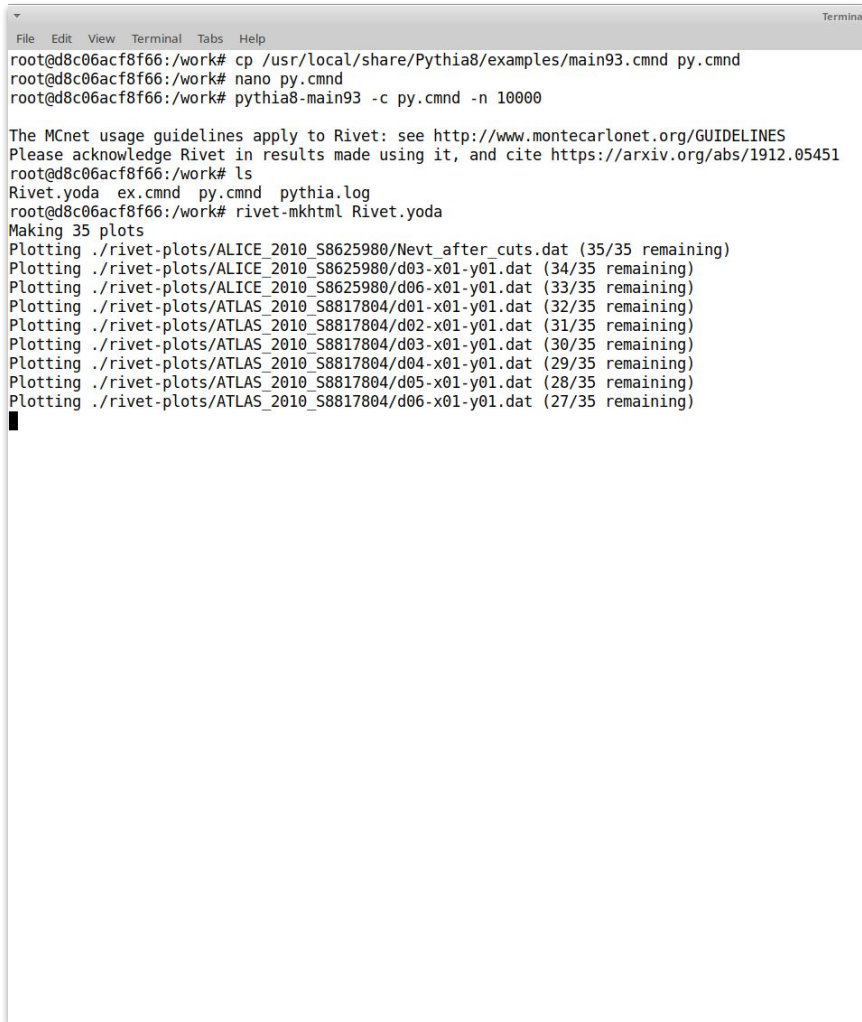
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root@d8c06acf8f66:/work# █
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root@d8c06acf8f66:/work# cp -r rivet-plots/ /out/
root@d8c06acf8f66:/work# █
```

Getting & using Rivet

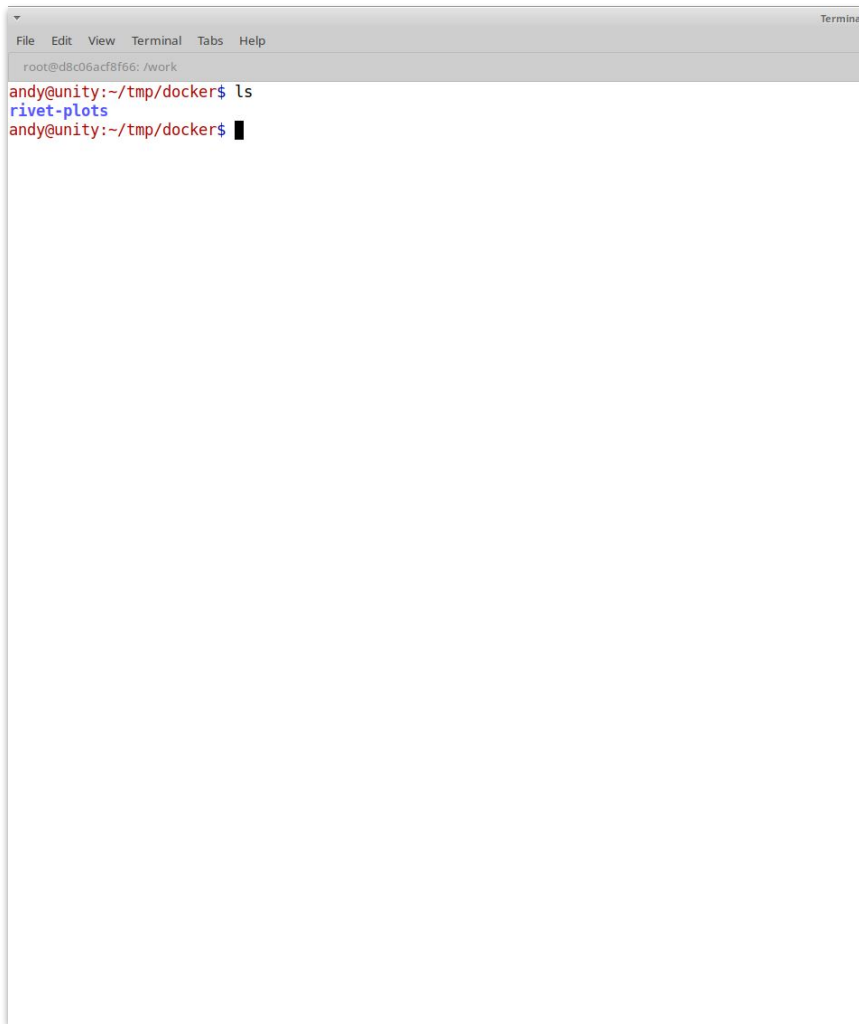
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```
File Edit View Terminal Tabs Help
root@d8c06acf8f66: /work

andy@unity:~/tmp/docker$ ls
rivet-plots
andy@unity:~/tmp/docker$
```

Getting & using Rivet

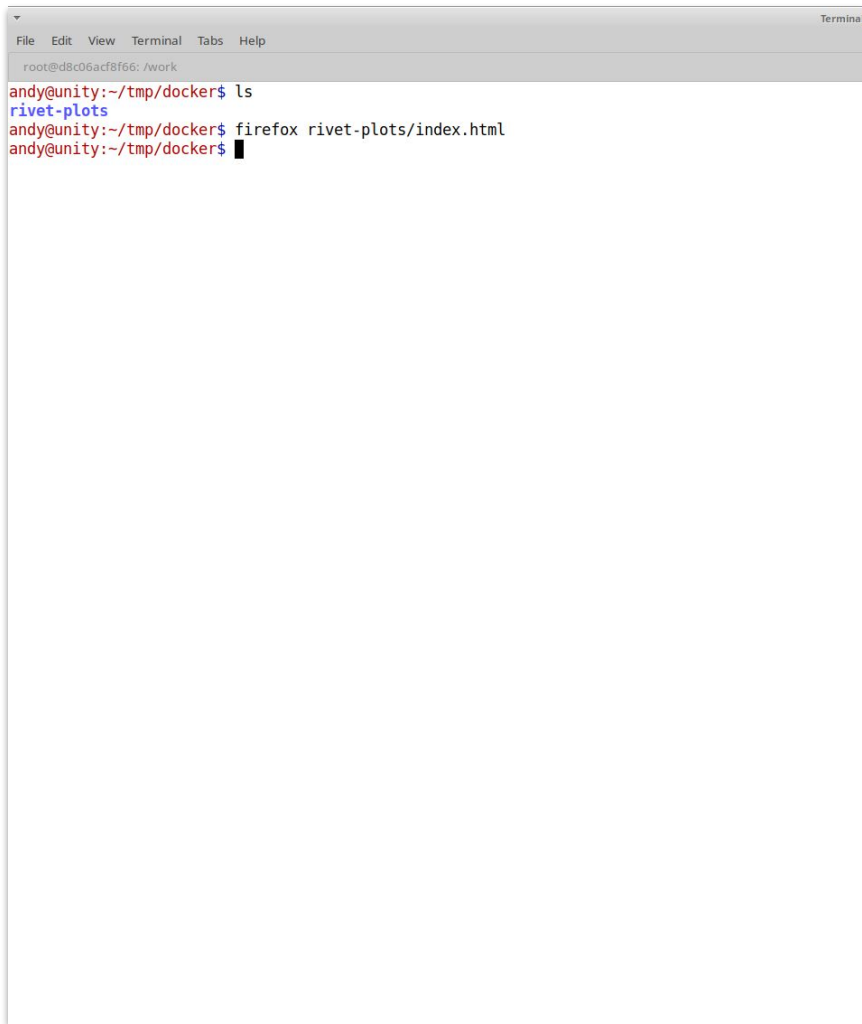
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andy@unity:~/tmp/docker$ ls
rivet-plots
andy@unity:~/tmp/docker$ firefox rivet-plots/index.html
andy@unity:~/tmp/docker$
```

Getting & using Rivet

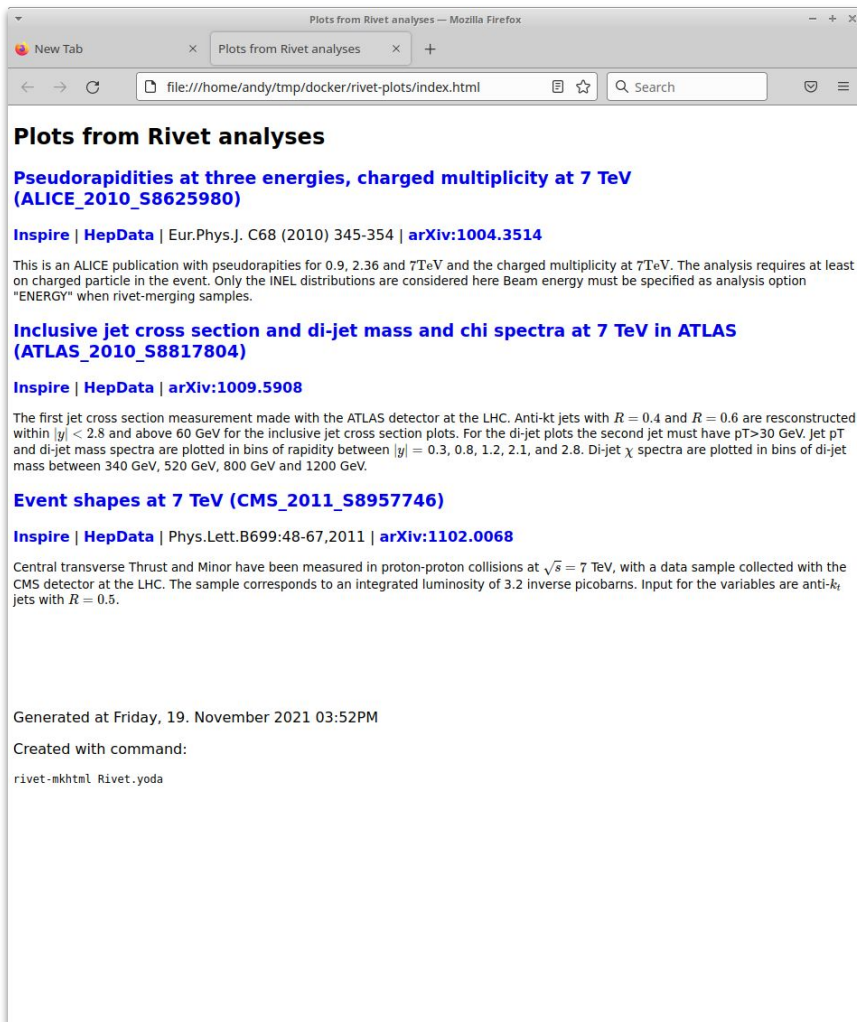
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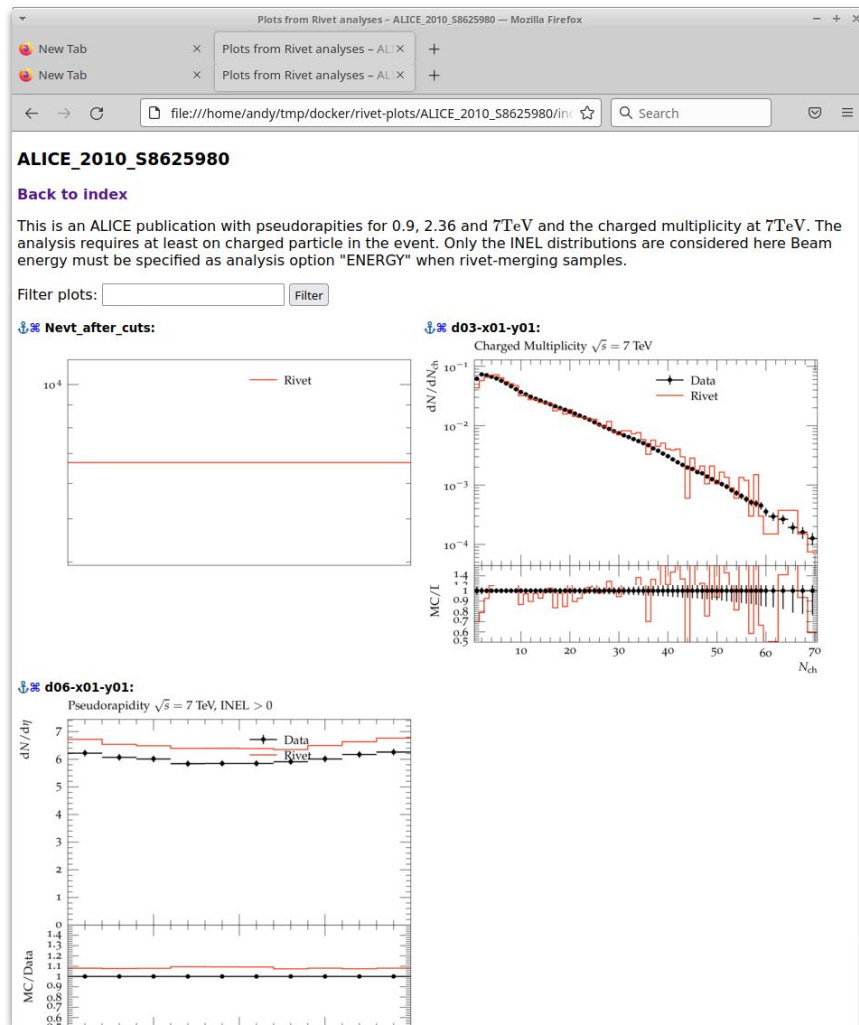
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Summary

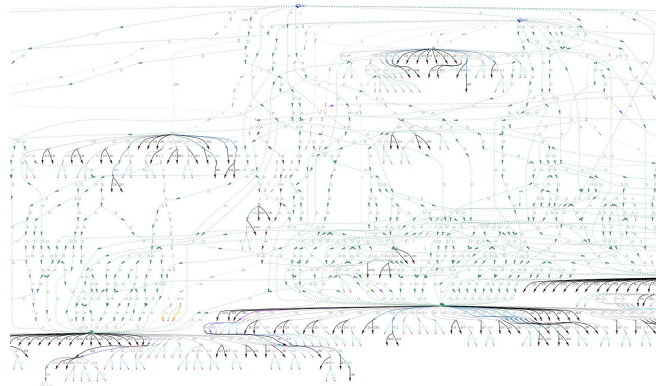
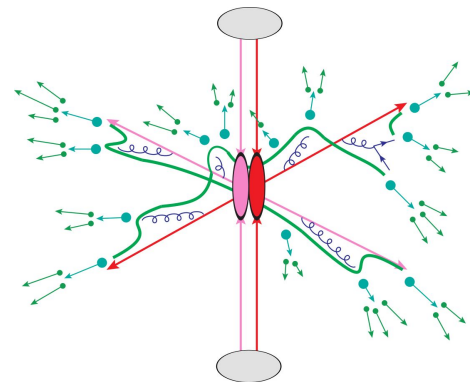
- ❖ Rivet arose from HERA experiment/MC author collaboration, in time for the LHC
- ❖ Like HZTool, its existence has spurred many other experiment/pheno activities, e.g.
 - MC development
 - MC tuning
 - PDF studies, EFT, global BSM fits...
 - Heavy-ion methods
 - And teaching / UG projects
- ❖ **An accelerator for analysis impact:** entry to many exp/theory studies via Rivet as common language
- ❖ **Refined HI and *ep* observable calculators:** Rivet is ready for EIC business! And happy to discuss & evolve...



Backup slides

MC generation

- ❖ **MC generation is where theory meets experiment**
 - The fundamental pp , pA , AA collision, *sans* detector
- ❖ **Components of an “exclusive” event-generator chain:**
 - QFT **matrix element** sampling at fixed-order in QCD
 - *Dressed* with approximate collinear splitting functions, iterated in factorised Markov-chain “**parton showers**”
 - FS parton evolution terminated at $Q \sim 1$ GeV: phenomenological **hadronisation** modelling
 - Mixed with **multiple partonic interaction** modelling
 - Finally particle **decays**, and other niceties
- ❖ **Modern HEP is hostage to shower MCs!**
 - The main mechanism for translating theory to experimental signatures, from QCD to BSM
 - Generally very complex modelling and output

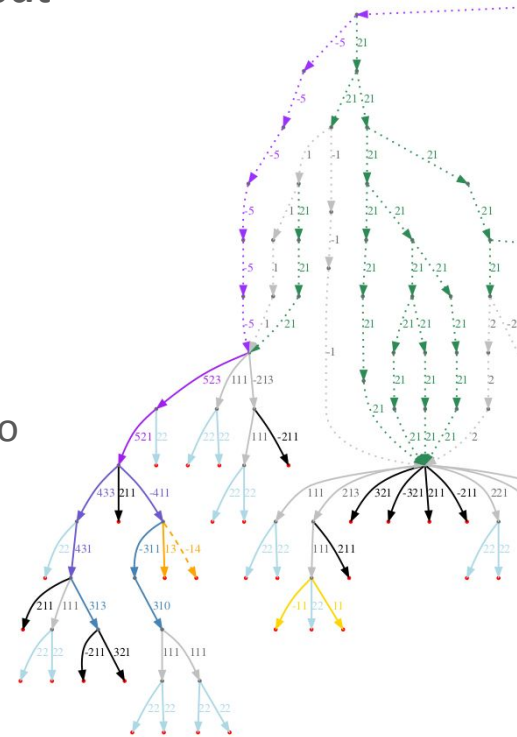


Physically safe analysis methods



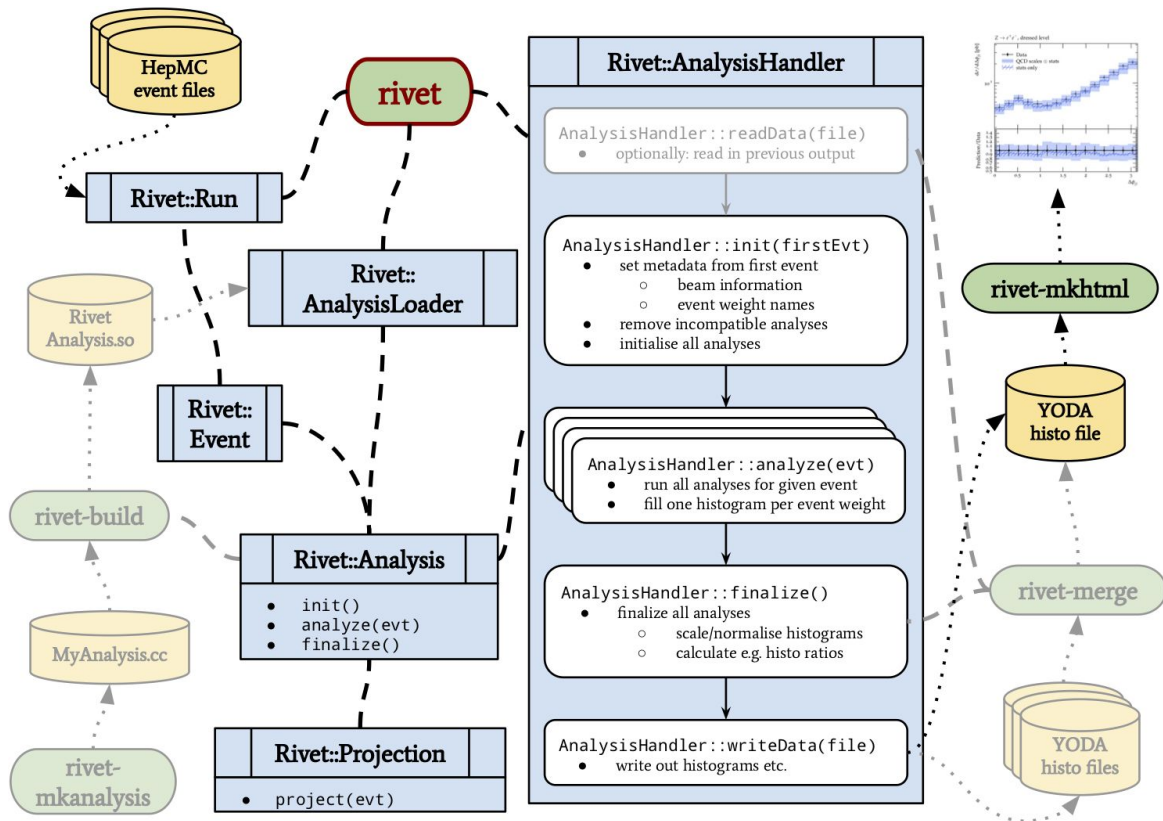
Avoiding unstandardised event-graph features was pragmatic, but led to some genuine physical insights:

- ❖ refining the “fiducial” idea, defining *unfolding targets*
- ❖ **Hadronisation as a “decoherence barrier”**
use the natural dividing line between the quantum-interfering hard process & semi-classical decays: ~ no tempting partons!
- ❖ **Bringing truth tagging closer to reco**
first releases used *b*-ancestry of jet constituents to set HF labels: too inclusive! \Rightarrow *associate* the hard-fragmenting, weakly-decaying *B*
- ❖ **Promptness/directness tests**
don’t identify a particle “from the hard process”; do it backward. Label as *indirect* via recursive checks for hadron parentage
- ❖ **Dressed leptons**
we now primarily *dress* truth leptons with their photon halo



The result

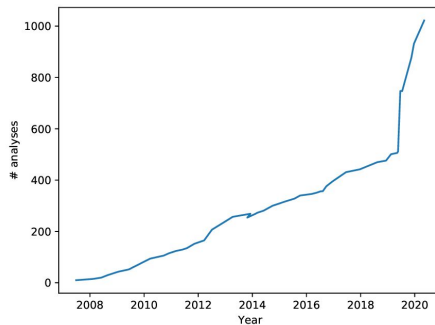
- ❖ As of Rivet v3.1.0
[arXiv:1912.05451](https://arxiv.org/abs/1912.05451)
- ❖ Streamlined set of tools from analysis coding to event processing to plotting (and other applications)
- ❖ And a key gateway to connect your analysis to theory (and back again)
- ❖ Let's review some of the early impacts...



The state we're in

❖ Version 3.1.0 crossed the 1000 analysis mark

A steady flow of analysis submissions, plus the occasional deluge of (mainly hadronisation) routines from Herwig!



❖ Official support from the LHC experiments is crucial

preservation = just part of how we do science; but still some way to go! Coverage monitoring:

❖ “New” features since the v1 vision: systematics multiweights, “perfect merging”, heavy ions, detector smearing functions, analysis options

Rivet analysis coverage (no searches, no heavy ion)

Rivet analyses exist for 845/4241 papers = 20%. 153 priority analyses required.

Total number of Inspire papers scanned = 7280, at 2020-07-02

Breakdown by identified experiment (in development):

Key	ALICE	ATLAS	CMS	LHCb	Forward	HERA	$e^+e^- (\geq 12 \text{ GeV})$	$e^+e^- (\leq 12 \text{ GeV})$
Rivet wanted (total):	72	111	126	183	43	461	765	647
Rivet REALLY wanted:	17	42	61	9	0	13	1	3
Rivet provided:	14/66 = 16%	135/246 = 55%	77/203 = 38%	13/196 = 7%	8/51 = 16%	9/470 = 2%	166/931 = 18%	344/991 = 35%

Show greylist Show blacklist

ALICE	ATLAS	CMS	LHCb	Forward	HERA	$e^+e^- (\geq 12 \text{ GeV})$	$e^+e^- (\leq 12 \text{ GeV})$	Tevatron	RHIC	SPS	Other
-------	-------	-----	------	---------	------	--------------------------------	--------------------------------	----------	------	-----	-------

ATLAS: Measurement of the $t\bar{t}$ production cross-section in the lepton+jets channel at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS experiment

Inspire ID: 1802524 arXiv ID: 2006.13076 Report IDs: CERN-EP-2020-096

Links: Inspire arXiv

ATLAS: Measurements of top-quark pair single- and double-differential cross-sections in the all-hadronic channel in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ using tt

Inspire ID: 1801434 arXiv ID: 2006.09274 Report IDs: CERN-EP-2020-063

Links: Inspire CDS arXiv

ATLAS: Measurements of the Higgs boson inclusive and differential fiducial cross sections in the 4ℓ decay channel at $\sqrt{s} = 13 \text{ TeV}$

Inspire ID: 1790439 arXiv ID: 2004.03969 Report IDs: CERN-EP-2020-035

Links: Inspire CDS arXiv HepData ATLAS_2020_11790439

ATLAS: Measurement of the Lund jet plane using charged particles in 13 TeV proton-proton collisions with the ATLAS detector

Inspire ID: 1790256 arXiv ID: 2004.03540 Report IDs: CERN-EP-2020-030

Links: Inspire DOI/Journal CDS arXiv HepData ATLAS_2020_11790256

ATLAS: Measurements of the production cross-section for a Z boson in association with b -jets in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS

Inspire ID: 1788444 arXiv ID: 2003.11960 Report IDs: CERN-EP-2020-022

Links: Inspire CDS arXiv

ATLAS: Measurement of isolated-photon plus two-jet production in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS detector

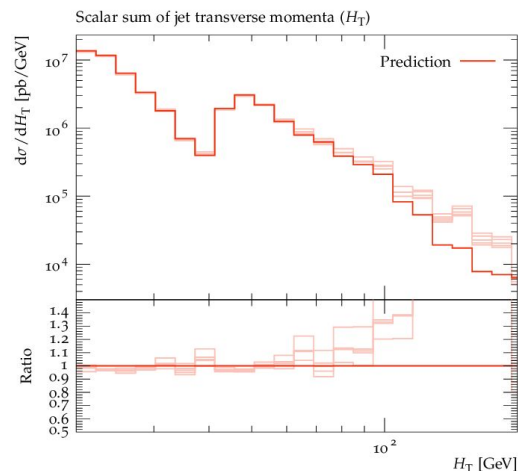
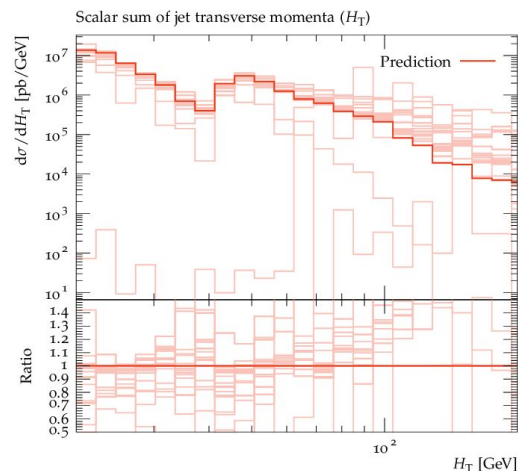
Inspire ID: 1772071 arXiv ID: 1912.09866 Report IDs: CERN-EP-2019-210

Links: Inspire CDS arXiv

ATLAS: A measurement of soft-drop jet observables in pp collisions with the ATLAS detector at $\sqrt{s} = 13 \text{ TeV}$

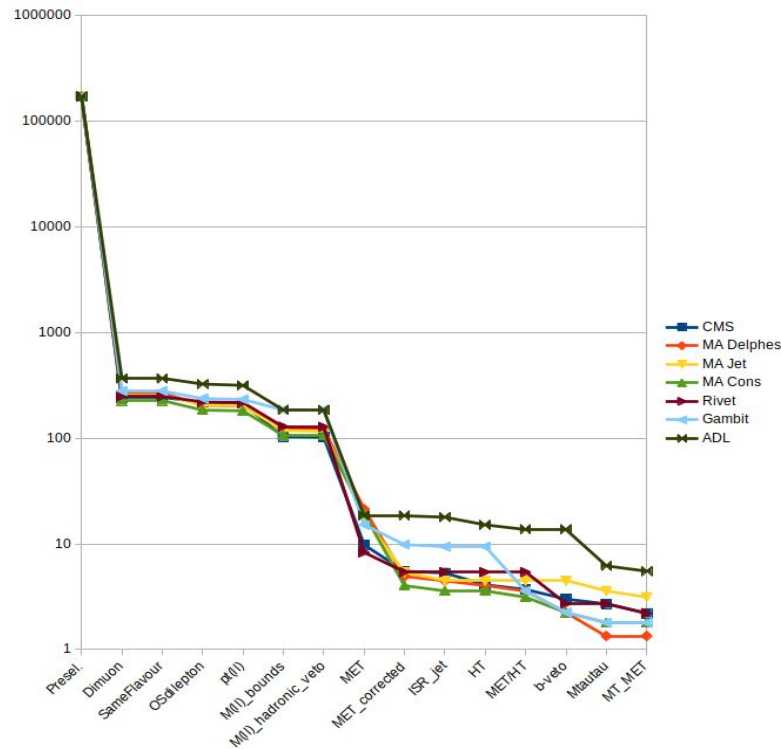
Multiweights and re-entry

- ❖ **MC weight vectors allow expression of increasingly complex theory uncertainties.** But a burden for analysis chains: have to propagate and correctly combine $O(200)$ weight streams!
- ❖ **Rivet 3: complex automatic handling of weights**
~invisible to users: data objects *look* like histograms etc. but are secretly multiplexed
- ❖ **Can now re-call finalisation to combine runs:**
RAW histogram stage preserves pre-finalize objects
⇒ “re-entrant” perfect data-object merging
Key for e.g. pA/pp or W/Z ratios, + BSM recasting
- ❖ **Data types are important:** glimpses of a fully coherent separation of semantics from presentation



Rivet and BSM-search recasting

- ❖ Rivet's main emphasis *isn't* BSM direct searches, but there's no reason not to
 - lots of experiment experience and support
 - efficient scaling-up to hundreds of analyses, with distinct phase-space specific detector/efficiency functions
 - can we do for BSM preservation what we did for measurement analyses?
- ❖ Friendly competition, mainly from/with MA5
 - all good tools, all geared to getting your analysis into pheno studies asap
 - but ours is best, obv... ;-)



BSM from “Standard Model”

❖ **Not being focused on *direct* searches doesn’t mean no interest in BSM!**

❖ **Particle-level measurements *can* achieve high model-independence**

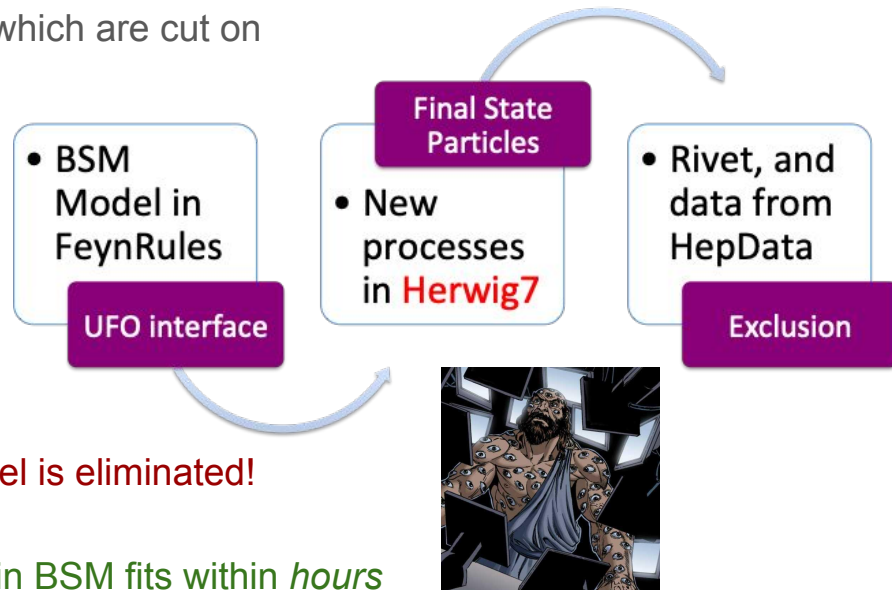
- Careful definition of fiducial cross-section
- Control distributions of “hidden variables” which are cut on
- Reduce model sensitivity in unfolding

❖ **Rivet used directly in e.g.**

- TopFitter top quark EFT fits;
- at core of ATLAS *VH* EFT fits; and...

❖ **Contur is getting particular uptake**

- Inject signal to “SM” measurements:
if it’d be statistically distinct, the model is eliminated!
- Rivet gives huge “synoptic” coverage:
a new result with Rivet code can be in BSM fits within *hours*



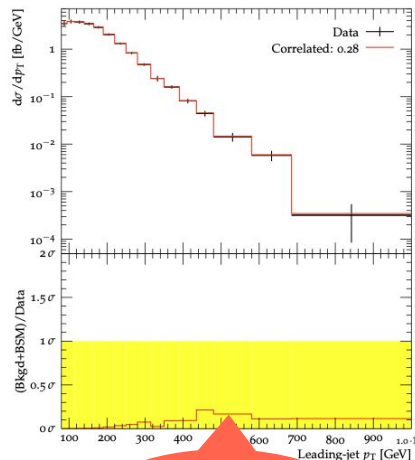
Contur



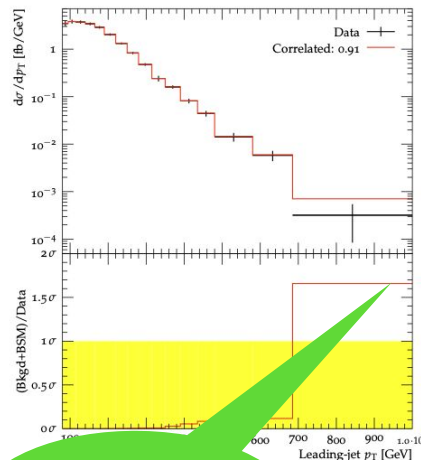
HT Louie Corpe

❖ Contur is “just” a wrapper on Rivet

- Ok, not just! You need to know which analyses are “safe”. Another reason for emphasis on final-states and *no cheating*
- In absence of unambiguous BSM, make zeroth-order assumption that data = SM
- Can be improved with high-precision SM theory predictions & uncertainties
- Signal-injection \Rightarrow care with e.g. ratios & profiles... cf. Rivet “perfect merging”
- Group analyses in stats-orthogonal “pools”. Use (expected) most-constraining element in the pool for setting limits — use correlations when possible to make “bigger” elements



Signal would have small effect wrt uncertainties, can't exclude it (28 % CL)



Signal would have large effects wrt uncertainties: can exclude at high CL

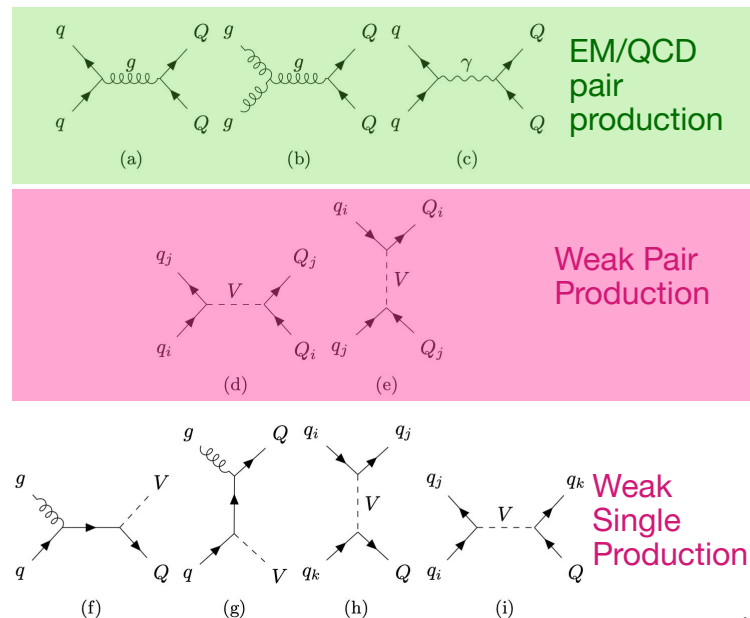
Contur BSM example

HT Louie Corpe

❖ Vector-like quarks [\[SciPost Phys. 9, 069 \(2020\)\]](#)

- Popular generic class of SM extensions, with new quark partners: $B^{-1/3}$, $T^{2/3}$, $X^{5/3}$, $Y^{-4/3}$
- Couple to SM via usual quark EM & strong couplings, but
 B, T : interact with W, Z or H via modified weak coupling
 X, Y : interact **only with W** via modified weak coupling: $X \rightarrow Wt$, $Y \rightarrow Wb$ always
- LHC searches mostly for 3rd gen, strong pair-production only!
- 4 masses, 1 overall coupling κ ,
 3 generational couplings ζ , 3 branching ratios ξ
 \Rightarrow rich collider phenomenology!

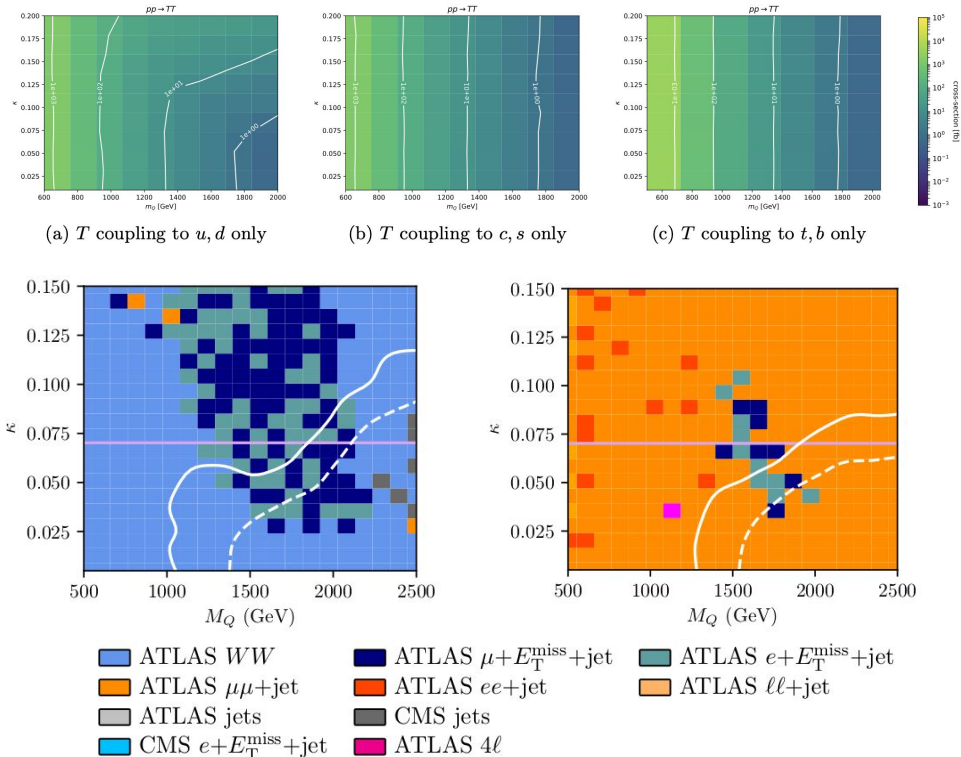
$$\begin{aligned} \mathcal{L} = & \kappa_B \left[\sqrt{\frac{\zeta_i \xi_W^B}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{B}_{L/R} W_\mu^- \gamma^\mu u_{L/R}^i] + \sqrt{\frac{\zeta_i \xi_Z^B}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{B}_{L/R} Z_\mu \gamma^\mu d_{L/R}^i] - \sqrt{\frac{\zeta_i \xi_H^B}{\Gamma_H^0}} \frac{M_B}{v} [\bar{B}_{R/L} H d_{L/R}^i] \right] \\ & + \kappa_T \left[\sqrt{\frac{\zeta_i \xi_W^T}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{T}_{L/R} W_\mu^+ \gamma^\mu d_{L/R}^i] + \sqrt{\frac{\zeta_i \xi_Z^T}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{T}_{L/R} Z_\mu \gamma^\mu u_{L/R}^i] - \sqrt{\frac{\zeta_i \xi_H^T}{\Gamma_H^0}} \frac{M_T}{v} [\bar{T}_{R/L} H u_{L/R}^i] \right] \\ & + \kappa_X \left[\sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{X}_{L/R} W_\mu^+ \gamma^\mu u_{L/R}^i] \right] + \kappa_Y \left[\sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{Y}_{L/R} W_\mu^- \gamma^\mu d_{L/R}^i] \right] + \text{h.c.}, \end{aligned}$$



VLQ pheno with Contur: 1st gen

- ❖ Even pair-production has κ -dependence via weak production initiated by valence quarks
- ❖ Weak Qq single-VLQ production can dominate over pair-prod!
- ❖ Different $W:Z:H$ BF's for T, B activate different analysis pools “automatically” due to Rivet coverage
- ❖ WW diboson mostly dominates, thanks to W and H decay channels
- ❖ “Injection” of ℓ +MET+jet events here from an unfolded VBF *control region*!

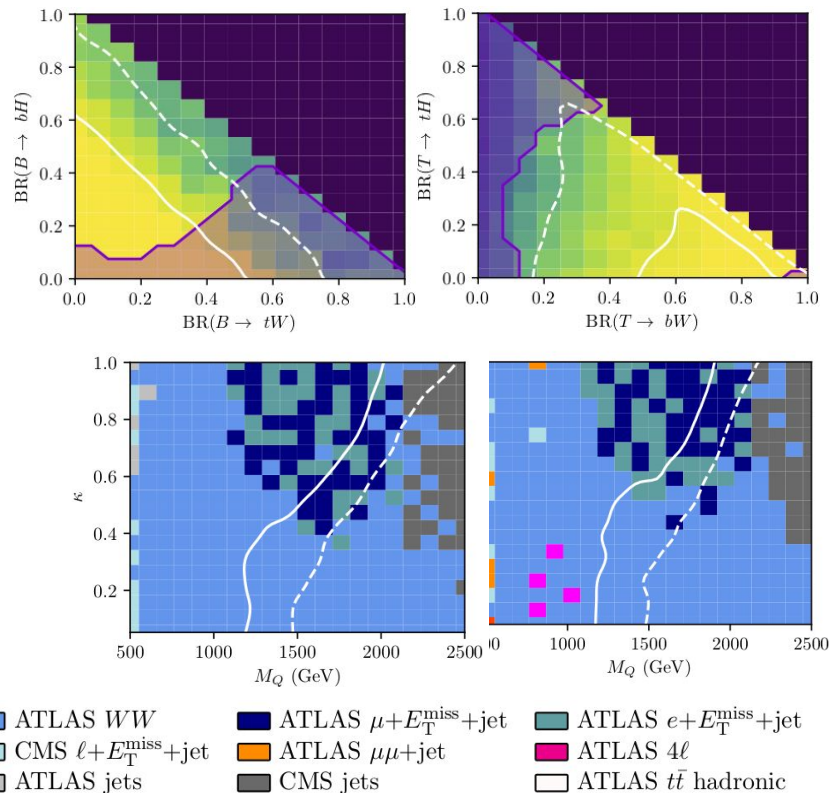
Pair-prod cross-sections



Exclusions complementary to non-collider limits

VLQ pheno with Contur: 3rd gen

- ❖ In pure T, B pair-production mode, diboson and ℓ +MET+jet “SM” analyses ~cover or complement direct searches wonderfully
- ❖ In general, for $W:Z:H = 0:1:0$, Tq and Xq production killed by tiny top-quark PDF: pairs at low- m_Q , Yq at high-mass. Decays always have a W (directly or via $T \rightarrow t Z \Rightarrow \ell$ +MET pool always dominates
- ❖ Rivet+Contur “SM” routines give powerful sensitivity to VLQs, even far from the benchmark search modes

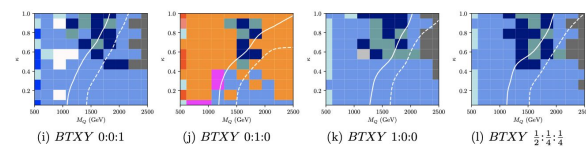
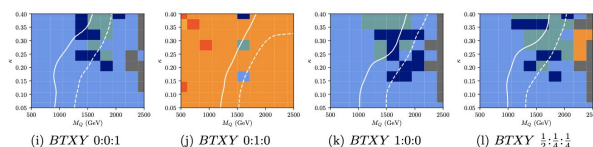
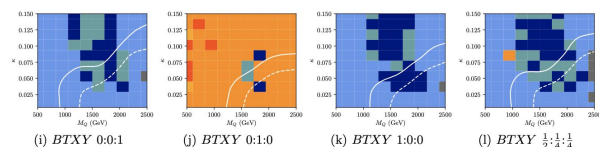
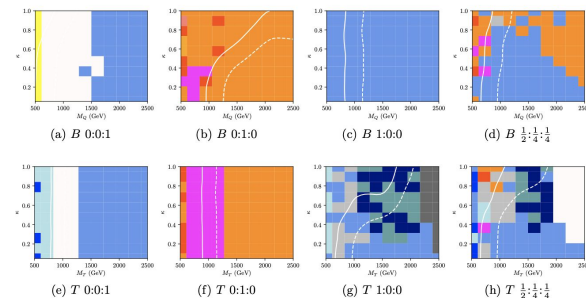
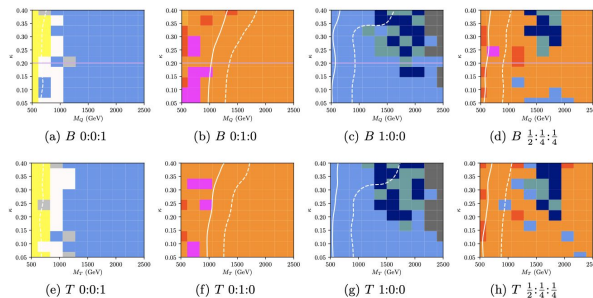
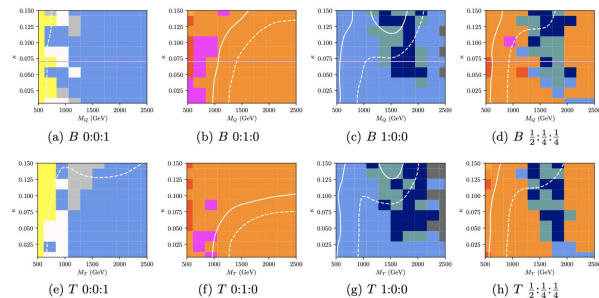


Generalising to 4 VLQs, still strong exclusions

More realistic models...

[singlets]

- ❖ Review requested a scan of realistic multiplets: 7 multiplets, each with 3 generational couplings, each with 4 W/H/Z-couplings, 300 points per scan, x 30,000 events!
- ❖ ~No problem! 1 month later...



ATLAS $t\bar{t}$ hadr
 ATLAS WW
 ATLAS ee +jet
 ATLAS 4ℓ
 ATLAS $\gamma\gamma$ & $\gamma+X$
 ATLAS $\mu+e_T^{miss}$ +jet
 ATLAS $\mu\mu$ +jet
 ATLAS jj +jet
 ATLAS jets
 ATLAS $e+e_T^{miss}$ +jet
 ATLAS $\ell\ell$ +jet
 CMS jets

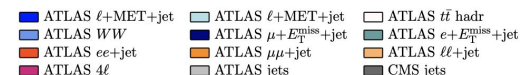
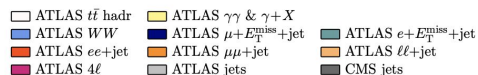
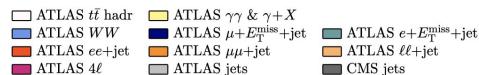
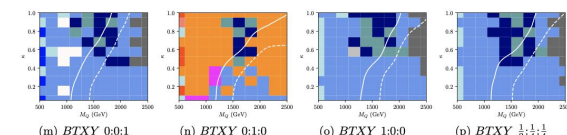
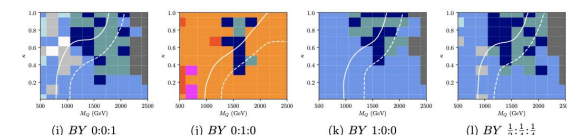
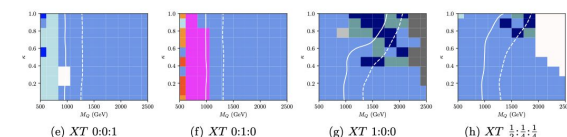
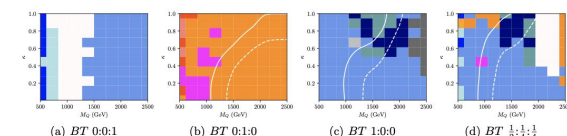
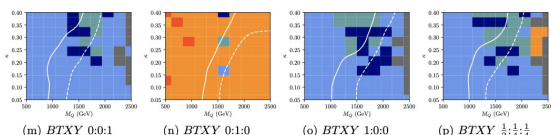
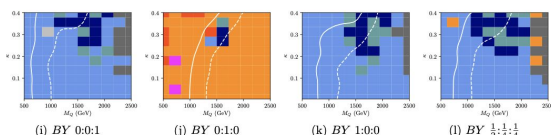
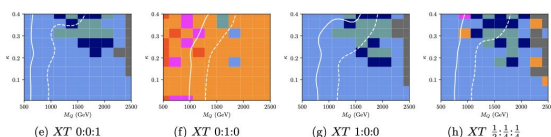
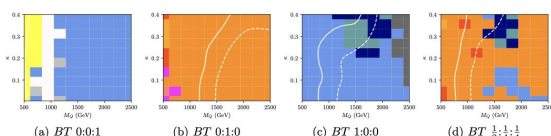
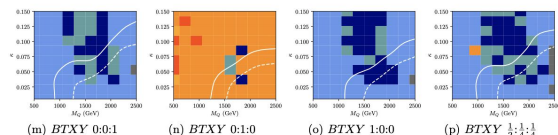
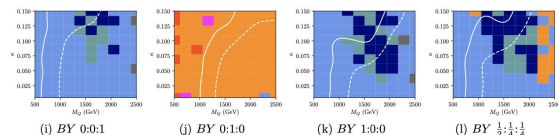
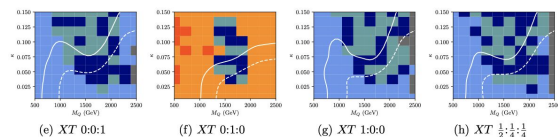
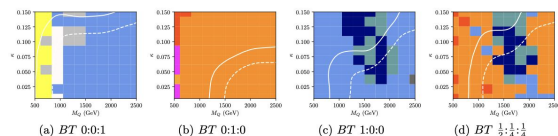
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 CMS jets

More realistic models...

[doublets]

- ❖ Review requested a scan of realistic multiplets: 7 multiplets, each with 3 generational couplings, each with 4 W/H/Z-couplings, 300 points per scan, x 30,000 events!



Harder, faster, stronger... moar BSM

- ❖ Now extending beyond 1D and 2D grids:
 - Rivet (and Herwig) as a function
 - Embed into adaptive scans
 - Higher param dimensionalities
 - Including beyond colliders, e.g. Gambit
- ❖ Rivet as a tool to probe new-observable sensitivity, e.g. in EFT models (TopFitter)
- ❖ Bootstrapping for victory: estimating statistical and systematic correlations (with SModelS, MadAnalysis5)

